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Genetic Diversity of Eggplant (*Solanum melongena* L.) Accessions Based on Morpho-Physiological Characteristics and Root System Architecture Traits

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ABSTRACT

The presence of genetic diversity leads to better adaptation of plants to different environments and enables researchers to select superior genotypes adapted to given culture conditions. In order to estimate the genetic diversity of eggplant, 22 accessions were obtained from the INRAe vegetable germplasm center and the National Plant Gene Bank of Iran and were planted in horticultural science station of University of Tehran, Karaj, in a randomized complete block design with three replicates. The number of flowers per plant and number of fruits per plant were higher in the MM00007 and FLT02 accessions, respectively. The maximum leaf area (190 cm^2 $plant^{-1}$) was recorded for MM 01597. Accessions FLT46, MM 0064, MM 00108 bis MM 01597 and MM 01010 revealed high variations in root characters. Higher number of root tips and maximum number of roots were assigned for FLT46, and average root orientation and steep root angle frequency for MM 01597 and MM 01010. The correlation of root angles frequency and root number could possibly be exploited in selection programs as factors indirectly involved in increasing yield and the number of flowers per plant. Based on all evaluated traits, genotypes FLT10, MM 01597, MM 01010, FLT46, and FLTE9012 could be used as parents for future eggplant breeding programs due to their desirable agricultural traits.

Keywords: Cluster, Correlation, Eggplant breeding, Factor analysis, Root characteristics.

INTRODUCTION

The existence of genetic diversity in plants is necessary in breeding programs in order to increase the chances of selecting desired genotypes. Accordingly, the study of genetic diversity among species and accessions within species is valuable for breeding and helps advance research programs (Orhan *et al*., 2007; Reim *et al*., 2012). The first step in identifying and differentiating native plant populations is to study the plant's phenotypical characteristics, because these characteristics can be measured easily and quickly and have many practical applications (Rotondi *et al*., 2003). Reducing genetic diversity, in addition to reducing the efficiency of breeding programs, causes genetic uniformity on farms and increases vulnerability to pests, diseases and environmental stresses. Wild relatives are a potential and valuable source of genetic diversity to which breeders pay special attention (Neel and Ellstr, 2003).

Eggplant (*Solanum melongena* L.) is one of the most important vegetable crops widely grown in central, southern, and southeastern Asia (Khaleghi *et al*., 2019). Total world annual production reached over 55 million tons in 2019. With an annual production of over 650 thousand tons, Iran is the fifth leading eggplant producer after China, India, Egypt, and Turkey (FAO stat, 2019). Although eggplant is a self-pollinated crop, because of variations in floral

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morphology it can be cross-pollinated. Furthermore, 30-40% of its fruit set is due to pollination by wind, contact and gravity, and the rest is insect-dependent (Sambandam, 1962). Variation among eggplant genetic resources of Japan and Iran according to phenotypic evaluation approved the existence of appropriate diversity (Khaleghi *et al*., 2019). Currently, eggplant production has been restricted to the cultivation of a few varieties and F1 hybrids because of their higher yield and improved fruit quality. This, however, has led to difficulties in eggplant breeding programs in that the genetic resources available for eggplant breeding have decreased (Cericola *et al*., 2013; Muñoz-Falcón *et al*., 2011).

Roots, as the link between the plant and the complex soil environment, play a key role in extracting water and nutrients from the soil (Meister *et al*., 2014). Root system architecture (RSA) refers to the shape and spatial order of the root system in the soil, which plays a major role in plant suitability, crop yield and agricultural productivity (Rogers and Benfey, 2015; Katuuramu *et al*., 2020). RSA is formed based on the interactions between genetic and environmental components and is affected by the total volume of soil that the root can explore (Rogers and Benfey, 2015; Bishopp and Lynch, 2015).

The aim of this study was to employ morphological and root system architecture traits for the determination of the genetic diversity in the present eggplant collection and the likely differences among the *S. melongena* genotypes collected from Iran and the INRAe vegetable germplasm center (France).

MATERIALS AND METHODS

Field Experiment

The experiment was carried out in the horticultural research station of University of Tehran situated in Karaj, 35° 98’ N, 50° 97’ E, at 1300 m elevation. In this study, seeds of 22 eggplant accessions were procured from the INRAe vegetable germplasm center and the National Plant Gene Bank of Iran (Table 1, Figure 1) and were sown in a 128-cell tray (4 cm^2 cells) filled with cocopeat and perlite (1:1 v/v). The trays were kept in a greenhouse with 16 h light at 20°C and supplied with a nutrient solution containing 20:20:20 NPK (N: 20-P: 20-K: 20+ trace elements) made by Green Italia solution (https://www.greenhasgroup.com).

Seedlings were grown for 2 months, then, transplanted to the field. The seedlings were immersed in metalaxyl fungicide solution before planting to reduce the incidence of soil fungal diseases. The seedlings of uniform size were transplanted into the experimental field in a completely randomized block design with three replications and five plants of each accession in each replicates on 10th June. The distances between and within the rows were about 50 cm and 40 cm. After planting, the irrigation schedule was every two days. Later, irrigation was reduced to twice a week, depending on the weather conditions and the plant establishment. Fruits were harvested at a range of developmental stages based on their size and skin color (around 30-40 days after flowering) depending on the accessions type; and in average, 11 harvests was done.

Morphological Characterization

Morphological traits were recorded from nine plants for each accession in each plot using descriptors developed by the International Board for Plant Genetic Resources (IBPGR, 1990) and UPOV (Union for Protection of New Varieties,) code system (2020). The studied traits included weight, length, perimeter, apical width, central width, tail end width, fruit number/plant and yield of fruits. Flower number/plant, leaf area, internode length, main stem length, number of aerial lateral branches were recorded and, for roots, three

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plants of each accession were used for evaluating the root system structural characters.

Preparing Roots for Imaging

After plant harvesting, 3-4 plants were selected from each accession of each plot, and soil was drilled to a width and depth of 50 cm and roots were removed from the soil. The root samples were washed for 30 minutes, and spread out on a broad black tray (1×1.5 m) and imaged as high-quality JPG files. Root system architecture was calculated from the flatbed images using Rhizo Vision Explorer v2.0.2 (Seethepalli *et al.*, 2021) based on diameter thresholds (in mm) of > 0.9, 0.3–0.9, and < 0.3, respectively.

Statistical Analysis

The data obtained from the experiments of this research were analyzed based on the statistical design using SAS statistical software version 9.4 and the comparison of the mean was performed using Duncan's multiple range tests at a probability level of 0.95% ($P< 0.05$). Correlations between root and leaf traits were determined using the Pearson correlation coefficient. In order to evaluate the information contained in the collected data, Principal Component Analysis (PCA) was carried out using SPSS (v. 21.0) statistics software. Cluster analysis was performed using Ward's method and the Euclidean distance and heat map dendrogram was performed by R software.

RESULTS

Aboveground Characteristics of Accessions

Fruit weight ranged from minimum of 14.07 to maximum of 431.33 g and belonged

Table 1. Accessions of eggplants obtained from the INRAe germplasm center (France) and National Gene Bank of Iran. Plant growth habit identifies by eggplant UPOVE.

Accession code	Origin	Plant growth habit
MM 00064	France	Semi-erect habit
MM 00108 bis	France	Erect
MM 00007	India	Prostrate
MM 00123	China	Erect
MM 00197	China	Semi-erect, Very early Flowering
MM 00960	Guadeloupe, Carribbean	Semi-erect, Slow growth
MM 01597	India	Erect
MM 01010	Malaysia	Erect, Primitive aubergine fruit type
FLT02	Iran-Hormozgan	Erect
FLT09	Iran --Fars	Semi-erect
FLT22	Iran- Ahvaz	Erect
FLT46	Iran-Bushehr	Semi-erect
FLT E.635	Iran-Ahvaz	Erect
FLT H.710	Iran-Yazd	Erect
FLT E.9011	Iran-Fras	Semi-erect
FLT E.9012	Iran-Birjand	Erect
FLT10	Iran-Fars	Semi-erect
FLT10	Iran-Bushehr	Bush
CHAHBOLAND1015	Iran-Neishabour	Erect
M-AbarKooh(M-AK)	Iran-Yazd	Semi-erect
MAL KARA	Collected from Khorasan	Semi-erect
YALDA	Collected from Isfahan	Erect

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Figure 1. Fruits diversity of *Solanum melongena* accessions.

to MM 01010 and FLT46, respectively. Among the studied accessions, Chahboland (CHB1015) had longer fruit with an average length of 28.75 cm *vs.* MM01010 with 3 cm recorded the minimum fruit length . The accessions showed large differences in fruit weight, number of fruits per plant, yield, number of flowers per plant, fruit apical width, fruit central width and number of aerial lateral branches. A higher variance per character indicates a wider range of values and thus increases the possibility of selection. Main stem length ranged from 34 to 130 cm (Table 2).

The results of this study showed that fruit perimeter, fruit apical width, fruit central width, fruit tail end width, fruit number /plant, and yield varied significantly amongst the accessions. The results of analyses (Table 2) demonstrated that number of flower/plant, leaf area, internode length, stem length, number of aerial lateral branches, and median number of roots were affected by eggplant accession ($P< 0.01$). The number of flowers/plant (152 n) and

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Table 2. Means comparison of eggplant accessions based on phenotypic characteristics.

Accession	Fruit weight (g)	Fruit length (cm)	Fruit perimeter (cm)	Fruit apical width (cm)	Fruit central width (cm)	Fruit tail end width (cm)	Number of fruit/ Plant	Yield (g plant^{-1})
MM 00064	374.86^{b}	11.18^{j}	31.96^{a}	6.32^{bc}	10.30^{b}	7.51^{a}	8.75^{g-i}	3280.7^{c-f}
MM 00108	150.31^{hi}	19.91^{de}	14.22^{hi}	3.33^{f}	4.35^{h}	3.32^{fg}	10.16^{g-i}	1525.8^{h-k}
MM 00007	44.91^{l}	10.99^{j}	10.58^{jk}	2.07^{i}	3.08^{ij}	1.93^{lm}	26.69^{b}	1198.1^{i-k}
MM 00123	106.22^{k}	17.76^{fg}	14.73^{h}	2.93^{fg}	4.54^{h}	2.24^{j-l}	9.00^{g-i}	963.7^{jk}
MM 00197	247.31^{e}	7.37^{k}	28.67^{b}	6.11^{bc}	9.31^{c}	7.24^{a}	5 ^{hi}	1232.4^{i-k}
MM 00960	216^{f}	17.06^{g}	21.61^{e}	3.94^{e}	6.84^{f}	4.34^{e}	4.16^{i}	890.6^{jk}
MM 01597	120.83^{jk}	25.23^{b}	11.54^{j}	2.48^{g-i}	3.50^{i}	2.36^{jk}	12.33^{f-i}	1511.3^{h-k}
MM 01010	15.51^{m}	3.00^{l}	10.12^{k}	1.95^{i}	2.97^{j}	1.65^{m}	21.71^{b-e}	341.4^{k}
FLT02	45.02^{l}	11.07^{j}	10.60^{jk}	2.23^{hi}	3.18^{ij}	1.95^{k-m}	35.54^{a}	1600.2^{g-k}
FLT09	338.71^{cd}	15.20^{h}	27.51^{bc}	6.01^{c}	8.95^{cd}	5.44^{c}	14.28^{d-g}	4867.3^{a}
FLT22	319.24^{d}	17.30^{fg}	25.23^{d}	5.27^{d}	8.05^{e}	4.62^{de}	13.27^{e-h}	4246.6^{a-c}
FLT46	413.31^{a}	13.48^{i}	32.20^{a}	6.60^{ab}	11.02^{a}	5.99^{b}	11.88^{g-i}	4900.9^{a}
FLT E.635	151.78^{hi}	22.63^{c}	14.28^{hi}	2.83^{fg}	4.46^{h}	3.08^{gh}	23.00^{bc}	3610.8^{b-e}
FLT H.710	186.20^{g}	18.62^{e-g}	17.00^{g}	3.99^{e}	5.30^{g}	3.66^{f}	16.33^{c-g}	3019.3^{c-f}
FLT E.9011	133.07^{ij}	23.75^{bc}	13.18^{i}	2.71^{gh}	4.01^{h}	3.17^{gh}	15.68^{c-g}	2057.5^{g-j}
FLT E.9012	134.78^{ij}	20.60^{d}	14.25^{hi}	2.75^{f-h}	4.45^{h}	2.78^{hi}	20.91^{b-f}	2811.5^{d-g}
FLT10	363.65^{bc}	10.93^{j}	33.09^{a}	7.12^{a}	11.02^{a}	7.17^{a}	8.47^{g-i}	3086.7^{c-f}
FLT110	328.15^{d}	14.19^{hi}	26.34^{cd}	5.78^{cd}	9.36^{c}	4.99^{d}	8.13^{g-i}	2712.6^{d-h}
CHB1015	212.27^{f}	28.75^{a}	13.44^{hi}	3.04^{fg}	4.11^{h}	3.37^{fg}	11.31^{g-i}	2402.1^{e-i}
M-AK	258.36^{e}	18.88^{ef}	20.16^{f}	4.18^{e}	6.40^{f}	4.39^{e}	11.23^{g-i}	2901.8^{d-f}
MAL KARA	345.90^{cd}	15.38^{h}	27.47^{bc}	5.26^{d}	8.65^{d}	5.42^{c}	13.98^{d-g}	4792.0^{ab}
Yalda	172.89^{gh}	27.45^{a}	13.88^{hi}	2.72^{gh}	4.28^{h}	2.58^{ij}	22.21^{b-d}	3897.7^{a-d}
CV%	7.21	5.6	4	7.93	4.49	5.92	3.99	15.85

Accession	Number of flower/ Plant	Leaf area (cm^{2} Plant^{-1})	Internode length (cm)	Stem length (cm)	Number of aerial lateral branches	Median number of roots	Maximum number of roots	Number of root tips
MM 0064	47.33^{e}	136.52^{d-g}	7.43^{a-d}	86.08^{b}	14.83^{hi}	7.75^{cd}	35.08^{a-d}	254.83^{ef}
MM 00108	43.44^{e}	130.63^{e-h}	5.51^{f-h}	85.22^{bc}	13.44^{hi}	12.22^{b-d}	52.11^{a}	289.78^{d-f}
MM 00007	152.41^{a}	92.18^{ij}	6.04^{d-h}	84.94^{bc}	44.63^{a}	9.16^{cd}	48.33^{a-c}	307.83^{c-f}
MM 00123	27.11^{ef}	135.58^{d-g}	8.16^{a}	77.22^{bc}	11.44^{ij}	8.5^{cd}	32.33^{a-d}	237.5^{ef}
MM 00197	19.06^{f}	115.76^{g-j}	4.96^{hi}	46.47^{d}	5.36^{j}	7.83^{cd}	28.66^{d}	171.22^{f}
MM 00960	18.00^{f}	171.09^{a-d}	3.78^{i}	47.16^{d}	15.33^{g-i}	19.5^{a}	48.33^{a-c}	444.5^{a-d}
MM 01597	110.00^{c}	190.13^{a}	8.22^{a}	108.33^{a}	19.16^{e-i}	10.33^{b-d}	41.16^{a-d}	261.33^{ef}
MM 01010	43.27^{e}	87.7^{1j}	5.63^{e-h}	67.51^{c}	24.55^{c-f}	11.88^{b-d}	53.44^{a}	367^{a-e}
FLT02	140.56^{ab}	122.58^{f-j}	7.87^{ab}	75.81^{bc}	13.61^{hi}	11.83^{b-d}	42.66^{a-d}	364.25^{a-e}
FLT09	71.77^{d}	126.99^{f-i}	6.17^{d-h}	78.76^{bc}	31.65^{bc}	8.33^{cd}	42.5^{a-d}	319.67^{c-f}
FLT22	72.02^{d}	133.21^{e-h}	7.63^{abc}	82.91^{bc}	23.52^{c-f}	9.33^{cd}	46.13^{a-d}	385.67^{a-f}
FLT46	49.33^{e}	124.32^{f-i}	6.56^{b-g}	87.33^{bb}	29.88^{b-d}	15.5^{ab}	53.83^{a}	505.83^{a}
FLT E.635	84.17^{d}	98.08^{h-j}	5.16^{gh}	85.66^{b}	23.16^{d-g}	8.83^{cd}	30^{cd}	272.83^{ef}
FLT H.710	76.73^{d}	173.06^{ab}	6.43^{c-g}	87.38^{b}	26.77^{b-e}	9.42^{cd}	50.97^{ab}	469^{a-c}
FLT E.9011	123.83^{bc}	98.27^{h-j}	4.81^{hi}	74.03^{bc}	29.71^{b-d}	10.08^{b-d}	40.77^{a-d}	276.28^{ef}
FLT E.9012	76^{c}	165.5^{a-e}	5.34^{f-h}	84.08^{bc}	27.25^{b-e}	13.33^{bc}	51.61^{ab}	482.28^{ab}
FLT10	28.58^{ef}	153.07^{b-f}	7.24^{a-d}	83.30^{bc}	20.38^{e-h}	7.33^{d}	39^{a-d}	323.56^{b-f}
FLT110	47.06^{e}	171.91^{a-c}	5.60^{e-h}	74.66^{bc}	13.7^{hi}	12.62^{b-d}	43.86^{a-d}	278.51^{ef}
CHB1015	47.88^{e}	127.48^{f-i}	7.33^{a-d}	82.31^{bc}	17.71^{f-i}	8.75^{cd}	41.16^{a-d}	328.08^{b-f}
M-AK	37.66^{ef}	182.43^{ab}	6.66^{b-f}	78.18^{bc}	20.97^{e-h}	8.44^{cd}	39.38^{a-d}	291.67^{d-f}
MAL KARA	69.56^{e}	163.9^{a-e}	6.99^{a-e}	82.65^{bc}	27^{b-e}	9.50^{cd}	48.25^{a-c}	383^{a-e}
Yalda	193.22^{d}	148.56^{b-g}	6.45^{c-g}	90.46^{b}	33.59^{b}	10.33^{b-d}	41.16^{a-d}	287.5^{d-f}
CV%	4.49	4.49	11.35	11.3	9.48	17.48	12.56	15.16

^{a} (a-m) Means followed by the same letter in a column are not significantly different according to Duncan test (P< 0.05). **(P< 0.01), * (P< 0.05), ns (P> 0.01).

Table2. Continued…

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Continue of Table 2. Means comparison of eggplant accessions based on phenotypic characteristics.

Accession	Total root length (mm)	Maximum root width (mm)	Average root diameter (mm)	Maximum root diameter (mm)	Root perimeter (mm)	Average root orientation (deg)	Shallow root angle frequency	Median root angle frequency	Steep root angle frequency
MM 0064	99.56^{d-f}	506.07^{a-e}	3.133^{a-c}	25.00^{a-c}	13159^{cd}	44.80^{a}	0.336^{bc}	0.336^{b}	0.327^{ab}
MM 00108	121.18^{a-e}	497.01^{a-e}	2.83^{b-e}	24.61^{a-d}	17860^{bc}	44.34^{ab}	0.345^{a-c}	0.327^{ab}	0.327^{ab}
MM 00007	121.91^{a-e}	426.46^{c-e}	2.63^{de}	21.43 ^{cd}	17024^{bcd}	43.95^{ab}	0.347^{abc}	0.333^{ab}	0.319^{ab}
MM 00123	96.43^{d-f}	371.67^{e}	2.56^{e}	20.50^{cd}	12067^{cd}	46.39^{a}	0.321^{bc}	0.314^{bc}	0.363^{a}
MM 00197	75.67^{f}	473.24^{b-e}	2.81^{b-e}	17.82^{d}	7848^{d}	41.86^{b}	0.388^{a}	0.313^{bc}	0.298^{b}
MM 00960	151.40^{a}	601.22^{a-c}	2.95^{a-e}	24.55^{a-d}	29088^{a}	43.54^{ab}	0.355^{ab}	0.328^{ab}	0.315^{b}
MM 01597	103.66^{c-f}	540.22^{a-e}	2.97^{a-e}	24.70^{a-d}	15496^{cd}	45.12^{a}	0.327^{bc}	0.340^{ab}	0.332^{ab}
MM 01010	135.44^{a-c}	676.13^{ab}	3.17^{a-c}	30.81^{a}	25067^{ab}	44.41^{ab}	0.362^{ab}	0.291^{c}	0.346^{ab}
FLT02	117.58^{b-e}	488.51^{b-e}	2.83^{b-e}	21.39^{b-d}	17928^{bc}	45.52^{a}	0.324^{bc}	0.333^{ab}	0.342^{ab}
FLT09	107.09^{c-f}	426.87^{c-e}	3.02^{a-e}	21.79^{b-d}	13742^{cd}	44.13^{ab}	0.343^{bc}	0.336^{ab}	0.319^{ab}
FLT22	121.66^{a-e}	592.12^{a-d}	3.05^{a-d}	25.22^{a-c}	18758^{bc}	44.18^{ab}	0.344^{bc}	0.333^{ab}	0.321^{ab}
FLT46	147.10^{ab}	533.42^{a-e}	2.97^{a-e}	25.89^{a-c}	25795^{ab}	44.42^{ab}	0.338^{bc}	0.338^{ab}	0.323^{ab}
FLT E.635	93.51^{f}	391.66^{de}	3.26^{ab}	26.25^{a-c}	11920^{cd}	46.16^{a}	0.310^{c}	0.344^{ab}	0.344^{ab}
FLT H.710	135.76^{a-c}	621.23^{a-c}	2.86^{a-e}	24.26^{a-d}	24847^{ab}	44.89^{a}	0.339^{bc}	0.320^{abc}	0.340^{ab}
FLT E.9011	107.92^{c-f}	511.71^{a-e}	3.22^{a-c}	24.72^{a-d}	14675^{cd}	44.92^{a}	0.338^{bc}	0.326^{ab}	0.335^{ab}
FLT E.9012	130.22^{a-d}	699.91^{a}	2.99^{a-e}	24.17^{a-d}	21320^{a-c}	44.12^{ab}	0.353^{a-c}	0.318^{abc}	0.327^{ab}
FLT10	105.18^{c-f}	540.22^{a-e}	3.05^{a-d}	24.32^{a-d}	14951^{cd}	44.31^{ab}	0.354^{a-c}	0.315^{bc}	0.330^{ab}
FLT110	116.69^{b-e}	414.60^{c-e}	2.64^{de}	22.89^{b-d}	16527^{b-d}	45.00^{a}	0.335^{bc}	0.328^{ab}	0.336^{ab}
CHB1015	116.75^{b-e}	477.50^{b-e}	3.04^{a-d}	26.27^{a-c}	17535^{bc}	44.52^{ab}	0.341^{bc}	0.327^{ab}	0.331^{ab}
M-AK	106.78^{c-f}	480.65^{b-e}	3.14^{a-c}	25.41^{a-c}	14191^{cd}	44.49^{ab}	0.336^{bc}	0.342^{ab}	0.321^{ab}
MAL KARA	119.70^{a-de}	457.25^{c-e}	2.77^{c-e}	27.42^{a-c}	18819^{bc}	44.97^{a}	0.335^{bc}	0.328^{ab}	0.336^{ab}
Yalda	106.48^{c-f}	604.14^{a-c}	3.33^{a}	27.71^{ab}	15145^{cd}	44.17^{ab}	0.337^{bc}	0.351^{a}	0.311^{b}
CV%	14.82	20.36	8.14	14.58	17.62	3.22	6.64	4.93	7.23

[a] (a-m) Means followed by the same letter in a column are not significantly different according to Duncan test (P< 0.05). **(P< 0.01), * (P< 0.05), ns (P> 0.01).

number of fruit/plant (35 n) were found to be highest in MM 00007 and FLT02 accessions, respectively. The maximum leaf area (190 cm^2 plant^{-1}) was recorded for MM 01597. The largest number of root tips was recorded in the FLT46 accession. The largest root width and diameter values were obtained in the MM 00064 and MM 00108bis accessions. In addition, the maximum number of roots, average root orientation, and steep root angle frequency were measured in the MM 01597 and MM 01010 accessions (Table 2).

Correlations among Traits

The correlation analysis was used to explore the existence of linear relationships between roots and the stem, which was visualized in a correlation matrix. The bivariate correlations between root and stem parameters are shown in Table 4. It was found that median number of roots negatively correlated with internode length (r= -0.48). The maximum number of roots showed a positive correlation with the number of aerial lateral branches (r= 0.44). The average root orientation was positively correlated with internode length (r= 0.45) and stem length (r= 0.52). Shallow root angle negatively correlated with fruit length (r= -0.48), internode length (r= -0.44) and stem length (r= -0.62). Median root angle frequency showed a positive correlation with fruit length (r=0.54), yield (r=0.53) and was negatively correlated with stem length (r= -0.45). Steep root angle frequency negatively correlated with fruit tail end width (r= -0.45) (Table 3).

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Table 3. Bivariate correlation between root and shoot traits of eggplant accessions.

traits	Fruit weight	Fruit length	Fruit perimeter	Fruit apical width	Fruit central width	Fruit tail end width	Number of fruits/ Plant	Yield	Number of flowers / Plant	Leaf area	Internode length	Stem length	Number of aerial lateral branches
Median Number of Roots	-0.08	-0.01	-0.08	-0.13	-0.05	-0.18	-0.04	-0.18	-0.11	0.18	-0.48*	-0.30	-0.03
Maximum Number of Roots	-0.07	-0.10	-0.13	-0.14	-0.12	-0.25	0.19	0.06	0.14	0.11	-0.16	0.14	0.44*
Number of Root Tips	0.12	-0.03	0.05	0.02	0.06	-0.08	0.19	0.29	0.05	0.21	-0.10	0.07	0.36
Total Root Length	-0.03	-0.07	-0.08	-0.11	-0.07	-0.22	0.11	0.02	0.02	0.14	-0.22	-0.03	0.33
Maximum Root Width	-0.14	-0.01	-0.13	-0.15	-0.14	-0.14	0.11	-0.06	-0.07	0.21	-0.17	0.00	0.17
Average Root Diameter	0.07	0.31	-0.04	-0.06	-0.06	0.03	0.13	0.3	-0.01	-0.13	-0.15	0.15	0.23
Maximum Root Diameter	0.01	0.20	-0.15	-0.19	-0.15	-0.20	0.13	0.24	-0.08	0.02	-0.01	0.31	0.32
Root Perimeter	-0.06	-0.10	-0.09	-0.12	-0.08	-0.21	0.08	-0.04	-0.05	0.17	-0.23	-0.08	0.24
Average Root Orientation	-0.21	0.30	-0.32	-0.33	-0.31	-0.42	0.31	0.09	0.28	0.03	0.45*	0.52*	0.01
Shallow Root Angle Frequency	0.09	-0.48*	0.27	0.28	0.25	0.36	-0.32	-0.27	-0.38	-0.12	-0.44*	-0.61**	-0.11
Median Root Angle Frequency	0.26	0.54*	0.06	0.05	0.07	0.04	0.14	0.53*	0.33	0.22	0.17	.0.45*	0.26
Steep Root Angle Frequency	-0.35	0.04	-0.37	-0.36	-0.35	-0.45*	0.54*	-0.18	0.13	-0.08	0.35	0.27	-0.12

** (P< 0.01), * (P< 0.05).

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Table 4. Qualitative traits of eggplant accessions.

Accession code	Purple color density in flowers	Presence of stem anthocyanins	Stem anthocyanin density	Presence of anthocyanin under the fruit calyx	Dominant color of the fruits	Dominant color density in fruits	Calyx thorns	Anthocyanin presence in calyx	Anthocyanin density in calyx	Calyx size	Fruit glossiness	Fruit overall shape	Fruit flesh color	Furrows on fruits
MM00197	5 (Moderate)	9 (Yes)	9 (Very high)	1 (No)	3 (Purple)	9 (Very dark)	3 (Low)	9 (Yes)	9 (Very high)	5 (Moderate)	5 (Moderate)	1 (Round)	2 (Green)	1 (No)
MM00123	3 (Pale)	9 (Yes)	9 (Very high)	1 (No)	3 (Purple)	7 (Dark)	1 (No)	9 (Yes)	9 (Very high)	3 (Matt)	3 (Matt)	5 (Stick shape)	2 (Green)	1 (No)
MM00064	5 (Moderate)	9 (Yes)	9 (Very high)	1 (No)	3 (Purple)	7 (Dark)	3 (Low)	9 (Yes)	7 (High)	5 (Moderate)	5 (Moderate)	1 (Round)	2 (Green)	1 (No)
MM01010	3 (Pale)	1 (No)	_	1 (No)	1 (White)	_	1 (No)	1 (No)	_	3 (Matt)	3 (Matt)	1 (Round)	2 (Green)	1 (No)
MM00960	3 (Pale)	1 (No)	_	9 (Yes)	3 (Purple)	9 (Very dark)	3 (Low)	1 (No)	_	7 (Glossy)	7 (Glossy)	3 (Reverse Oval)	2 (Green)	1 (No)
MM00108bis	3 (Pale)	9 (Yes)	7 (High)	9 (Yes)	3 (Purple)	9 (Very dark)	5 (Moderate)	9 (Yes)	3 (Low)	7 (Glossy)	7 (Glossy)	5 (Stick shape)	2 (Green)	1 (No)
MM01597	3 (Pale)	1 (No)	_	1 (No)	2 (Green)	5 (Moderate)	1 (No)	1 (No)	_	7 (Glossy)	7 (Glossy)	7 (Cylindrical)	2 (Green)	1 (No)
MM00007	5 (Moderate)	9 (Yes)	7 (High)	1 (No)	3 (Purple)	5 (Moderate)	9 (Very high)	9 (Yes)	5 (Moderate)	3 (Matt)	3 (Matt)	5 (Stick shape)	2 (Green)	1 (No)
Yalda	3 (Pale)	9(Yes)	3 (low)	9 (Yes)	3 (Purple)	9 (Very dark)	1 (No)	1 (No)	_	7 (Glossy)	7 (Glossy)	7 (Cylindrical)	2 (Green)	1 (No)
FLT09	3 (Pale)	9 (Yes)	1 (very low)	9 (Yes)	3 (Purple)	9 (Very dark)	1 (No)	1 (No)	_	7 (Glossy)	7 (Glossy)	1 (Round)	2 (Green)	1 (No)
FLT02	3 (Pale)	9 (Yes)	9 (Very high)	1 (No)	3 (Purple)	5 (Moderate)	3 (Low)	9 (Yes)	7 (High)	5 (Moderate)	5 (Moderate)	5 (Stick shape)	2 (Green)	1 (No)
FLT22	3 (Pale)	1 (No)	_	9 (Yes)	3 (Purple)	9 (Very dark)	3 (Low)	1 (No)	_	7 (Glossy)	7 (Glossy)	4 (Pear shape)	2 (Green)	1 (No)
Chah Boland	3 (Pale)	1 (No)	_	9 (Yes)	3 (Purple)	9 (Very dark)	3 (Low)	1 (No)	_	7 (Glossy)	7 (Glossy)	7 (Cylindrical)	2 (Green)	1 (No)
FLTE9011	3 (Pale)	1 (No)	_	9 (Yes)	3 (Purple)	5 (Moderate)	1 (No)	1 (No)	_	3 (Matt)	3 (Matt)	7 (Cylindrical)	2 (Green)	1 (No)
FLTE635	3 (Pale)	9 (Yes)	5 (Moderate)	9 (Yes)	3 (Purple)	9 (Very dark)	3 (Low)	9 (Yes)	1 (Very Low)	7 (Glossy)	7 (Glossy)	7 (Cylindrical)	2 (Green)	1 (No)
FLTH710	3 (Pale)	1 (No)	_	9 (Yes)	3 (Purple)	9 (Very dark)	3 (Low)	1 (No)	_	7 (Glossy)	7 (Glossy)	6 (Long oval)	2 (Green)	1(No)
FLTE9012	7 (Dark)	9 (Yes)	7 (High)	9 (Yes)	3 (Purple)	3 (Pale)	1 (No)	9 (Yes)	1 (Very Low)	3 (Matt)	3 (Matt)	7 (Cylindrical)	1 (White)	1 (No)
FLT110	5(Moderate)	9 (Yes)	9 (Very high)	9 (Yes)	3 (Purple)	9 (Very dark)	1 (No)	9 (Yes)	5 (Moderate)	7 (Glossy)	7 (Glossy)	4 (Pear shape)	2 (Green)	7 (Many)
Abarkooh	3 (Pale)	1 (No)	_	9 (Yes)	3 (Purple)	3 (Pale)	3 (Low)	1 (No)	_	5 (Moderate)	5 (Moderate)	6 (Long oval)	2 (Green)	1 (No)
FLT10	5 (Moderate)	9 (Yes)	5 (Moderate)	1 (No)	3 (Purple)	7 (Dark)	1 (No)	9 (Yes)	7 (High)	7 (Glossy)	7 (Glossy)	1 (Round)	1 (White)	1 (No)
FLT46	3 (Pale)	1 (No)	_	9 (Yes)	3 (Purple)	9 (Very dark)	3 (Low)	1 (No)	_	7 (Glossy)	7 (Glossy)	4 (Pear shape)	2 (Green)	9 (So many)
Mal Kara	3 (Pale)	1 (No)	_	9 (Yes)	3 (Purple)	9 (Very dark)	3 (Low)	1 (No)	_	7 (Glossy)	7 (Glossy)	1 (Round)	2 (Green)	1 (No)

Qualitative Traits

There were high variations in evaluated qualitative traits (Table 4). All the traits related to flower color, stem calyx and fruit exhibited noticeable variation among the germplasm, except for furrows on fruits and fruit flesh color. The dominant color density in fruits was distributed over four categories: very dark, dark, moderate, and pale. Stem anthocyanin density variation was categorized as very high, high, low, very low, and moderate in the studied germplasm. The presence of anthocyanins under the fruit calyx and anthocyanin presence in stems showed high variation; in particular, MM00197, MM00123, MM00064, FLT02 and FLT110 had high levels of stem anthocyanins. The calyx size was the most variable with the following classes: very small (MM00197), moderate (MM00123), large (MM00960), and very large (Yalda).

Root Traits

The data reported here indicated which eggplant genotypes had the highest total root length values and sufficient total root surface area. Several root traits showed significant genetic variation such as number of root tips, total root length, maximum root width, average root diameter, maximum root diameter, root perimeter, average root orientation, shallow root angle frequency, medium root angle frequency and steep root angle frequency (Table 2, Figure 2). Accession FLT46 collected from Iran (Bushehr) had the largest number of root tips. Accessions MM 00064 and MM 00108 bis, both collected in France, had the largest root width and diameter values. Accessions MM 01597 and MM 01010 collected from India and Malaysia, respectively, had the largest maximum number of roots, average root orientation and steep root angle frequency (Table 2, Figure 2).

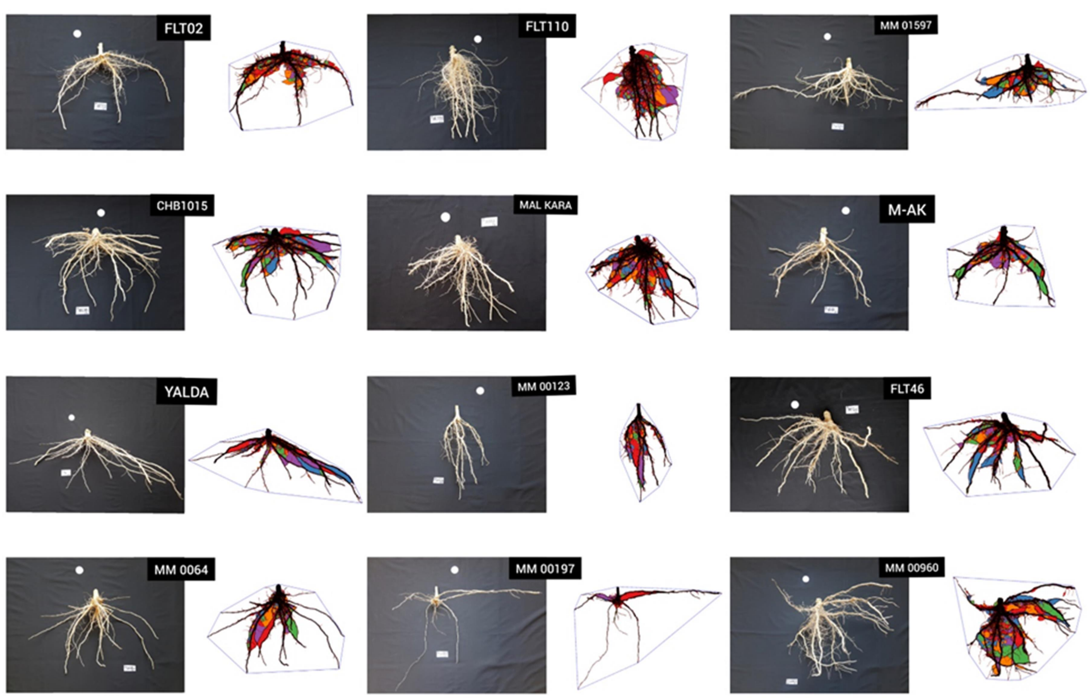

Figure 2. Images displaying root traits of eggplant by RhizoVision.

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Heat Map Analysis

Heat map analysis allowed the assessment of distance and clarified some of the relationships among the 22 accessions of the studied eggplants. Initially, a dendrogram was produced with two main clusters where cluster one (I) was divided into two main sub-clusters. The first group in cluster I mainly included accessions characterized by stem length, maximum number of roots, average root orientation, shallow root angle frequency, medium root angle frequency and steep root angle frequency. The second group in cluster I was characterized by fruit weight, fruit length, fruit perimeter and number of root tips. It seems that the accessions in this cluster can be used in breeding programs aimed at increasing eggplant yield, as one of its most important traits. Besides that, the MM 00197 accession of the second group of the first cluster was placed in a separate sub-group that was characterized by the number of aerial lateral branches and lowest number of fruits per plant. Although MM 00197 accessions showed the lowest mean values for the number of fruits per plant and number of flowers per plant, they had the highest fruit tail end width: as this trait is important for breeders, its inclusion is recommended in breeding programs. Cluster II included accessions that were characterized by their internode length, total root length, maximum root width, average root diameter and root perimeter (Figure 3).

DISCUSSION

Morpho-Physiological Diversity of Aboveground Traits

The results of this study showed that fruit traits were more variable in the case of shape, color and size, which determine other quantitative characters such as fruit weight and yield. There was an accession with round, bitter, small, and yellow color fruit belonged to MM 0007 with the minimum yield. Fruit shape, presence of anthocyanin and purple pattern in calyx and fruit assigned more variable code numbers among accessions. The differences in fruit color, size, shape and diameter have been evaluated previously for eggplant genotypes (Uddin *et al*., 2015; Khaleghi *et al*., 2019; Prohens *et al*., 2005; Tumbilen *et al*., 2011). The first cultivated eggplants were genetically diverse and during breeding/domestication changes in fruit shape, size, and color were introduced, while bitterness and spikiness were reduced due to breeding operations such as pollination, hybridization, mutation, and selection (Frary *et al*., 2007). Fruit size, shape, color, and weight vary widely in Turkish eggplant (Tumbilen *et al*., 2011; Cakir *et al*., 2017). Cericola *et al*. (2013) observed the greatest variety in eggplant fruit size, weight, shape and curvature as well as its flesh color. Uddin *et al*. (2015) found that eggplant cultivars exhibited significant variation in size, shape, and color of both flowers and fruits. Fruit yield varied from 2,410 to 4,023 g plant^{-1} among the eggplant varieties (Khaleghi *et al*., 2019). The range of fruit number per plant (2.5–42.2) measured in this study was higher than those reported in previous studies. While Prohens *et al*. (2005) reported a range of 2-11 fruits in eggplant cultivars, Polignano *et al*. (2010) reported an average of 2.6 fruits per plant in their study of 55 cultivars. Regarding plant height, the range observed in this study was consistent with that reported by Prohens *et al*. (2005) who studied a collection of 27 eggplant accessions.

The correlation coefficients calculated indicate that median root angle frequency and as well as average root diameter could possibly be exploited in selection programs as factors indirectly involved in increasing yield and the number of flowers per plant. Moreover, positive and significant correlations were established between fruit central width and fruit tail end width with shallow root angle frequency. It was reported that plant width, leaf dry matter,

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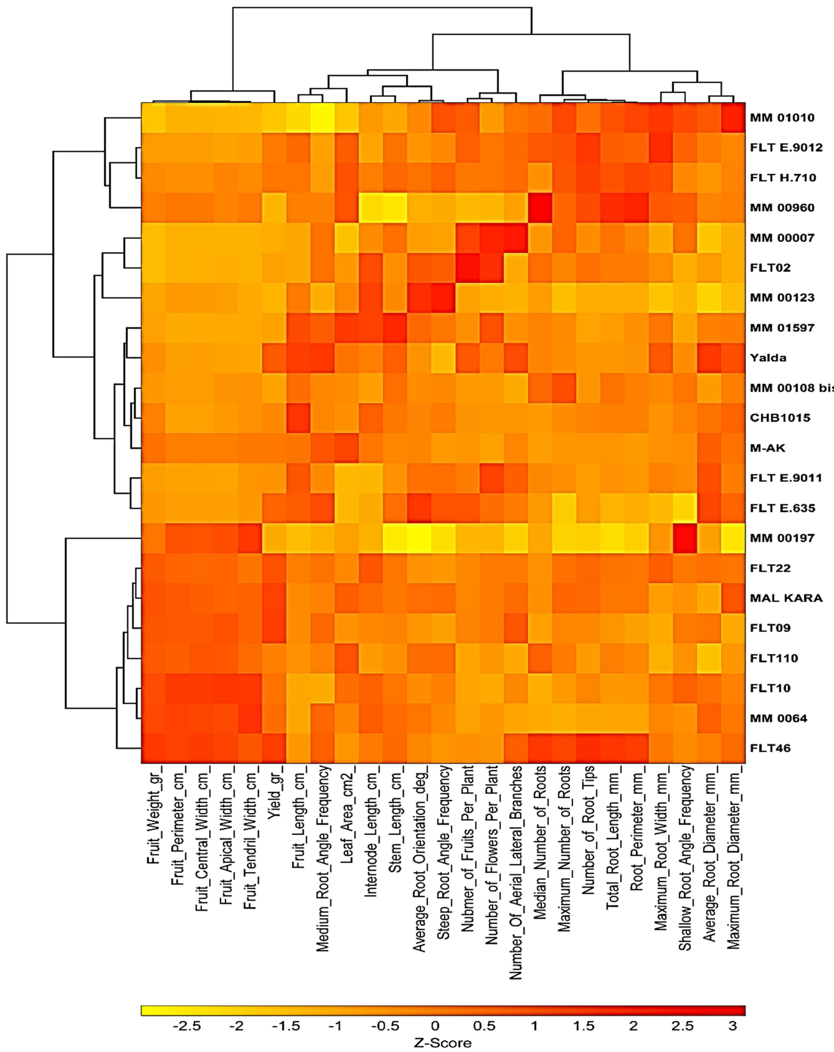

Figure 3. Heat map clustering of eggplant accessions using aboveground and underground characters.

number of short style flowers, number of fruits per plant, plant growth habit and leaf blade lobbing had positive correlations with fruit yield per plant in eggplant genotypes (Khaleghi *et al*., 2019). Root inter-lateral distance correlates with root fresh weight in *Solanum melongena* L. (Salinier *et al*., 2019). Correlations between leaf area growth rate and root elongation rate were found within the root systems and between shoot and root in Solanaceae such as eggplant (Bui *et al*., 2015).

Interestingly, we found a positive significant correlation between median root angles, steep root angles with fruit yield, fruit number, and fruit length. Our data indicated that sallow root angles and median and maximum root number associated with shorter internode length and higher lateral branches. While the observed results of increases in yield and fruit number are consistent with correlation between roots and shoot relation, it is possible that the traits we have examined are genetically,

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physiologically, or phylogenetically linked with other traits we did not investigate. For example, the increases in yield may be primarily due to aboveground traits, not the root traits, although there is evidence that above- and belowground traits are not highly linked and can evolve independently (Weiner *et al*., 2017). Root median and steep angles frequency showed the root distribution in deep soil layer and availability of nutrient and water. In some respects lateral roots and shoots can be controlled by genes regulating auxin production in root and shoot nodes (Roychoudhry and Kepinski, 2015). A strong coupling between root and shoot growth and dimension have also been reported in wild barley and *Arabidopsis* (VanRijn *et al*., 2000; Bouteillé *et al*., 2012).

Based on the squared coefficients of the estimated Euclidean distance, the highest genetic distance was obtained between FLT02 and MM0960 accessions; these accessions stood out because of their median number of roots, total root length, average root diameter, and root perimeter. Regarding the heat map classification, root architecture characters alongside with fruit traits were more effective for discriminating accessions. Cluster analysis grouped eggplant varieties into four clusters, in which fruit number and yield per plant had the higher values in the grouping (Khaleghi *et al*., 2019).

Root Traits

The root architecture traits chosen for this study showed, nearly without exception, variability among accessions in the same environmental condition. The range of variability for root and root tips number and root angles (shallow and steep) were amenable and valuable characteristics to breeding. In Solanaceae family members such as eggplant, the primary root system is complemented by a strong adventitious root that appears near their base, and contains a collection of fast-growing roots with large apical diameters (Bui *et al*., 2015). Improving water and food efficiency and plant productivity with future limited water resources depends on plant roots. Therefore, increasing knowledge about the dynamics and architecture of the root system is very important. Careful study of the roots has not been carried out in breeding programs and can be one of the important research goals of many products, including eggplant. Most of the germplasm diversity in the world for eggplant originates from Asia. Numerous studies have shown that root traits and characteristics such as root length have a high correlation with water tolerance (Comas *et al*., 2012; Uga *et al*., 2013). Other traits such as root density, root diameter, root emergence angle, capillary root density, and biomass ratio between shoot and root are also important (Comas *et al*., 2012). Considering fruit yield, maximum root number, root tips, root length and root angles we identified two accessions, namely, FLT46 from Bushehr and FLT9012 from Birjand that could be used for grafting and pre-breeding program.

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تنوع ژنتیکی توده های بادمجان (*Solanum melongena* L.) بر اساس صفات مورفوفیزیولوژیکی و معماری ریشه

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چکیده

وجود تنوع ژنتیکی منجر به سازگاری بهتر گیاهان به شرایط محیطی متفاوت شده و محققین را قادر می سازد تا ژنوتیپ های برتر سازگار شده به این شرایط را انتخاب کنند. به منظور بررسی تنوع ژنیکی بادمجان، ۲۲ توده که از مرکز ژرم پلاسم سبزیها در فرانسه - موسسه اینرا و بانک ژن ملی ایران تهیه شد و در ایستگاه تحقیقات باغبانی دانشگاه تهران در طرح بلوک های کامل تصادفی با سه تکرار کشت شدند. بیشترین تعدا گل در هر بوته و تعداد میوه روی بوته به ترتیب در توده هایMM00007 و FLT02 بود. بیشترین سطح برگ (۱۹۰cm^2) برای توده MM01597 ثبت شد. توده‌های FLT46، MM0064،MM 0018bis، mm 01597 و

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MM01010 بیشترین تنوع در صفات ریشه نشان دادند. بیشترین تعداد نوک ریشه و بیشترین تعداد ریشه برای FLT46، میانگین تغیر جهت و تعدد زاویه ای در سطوح مختلف برای MM01597 و MM01010 اختصاص یافت. همبستگی زوایای مختلف و تعداد ریشه ها بعنوان فاکتورهای غیر مستقیم در برنامه های انتخاب جهت افزایش عملکرد، تعداد میوه و تعداد گل در بوته مد نظر قرار گیرد. بر اساس تمام صفات ارزیابی شده می‌توان توده‌های FLT10،MM01597، MM01010، FLT46، FLTE9012 بعنوان والدین انتخابی برای برنامه های اصلاحی بدلیل صفات رزاعی مطلوب مورد استفاده قرار داد.

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